Experiments on the Dark Space in Vacuum Tubes.

By Sir William Crookes, D.Sc., F.R.S.

(Received January 1,—Read January 24, 1907.)

1. When an induction spark passes through an exhausted vacuum tube we see, firstly, a luminous layer coating the cathode, next a dark space; beyond the outer edge of this dark space comes a luminous envelope, then another blank, sometimes called "Faraday's dark space," and, lastly, the positive column. Between the second dark space and the positive column, if the exhaustion is suitable, stratifications occur. In the present paper I speak of the first dark space extending from the luminous layer on the cathode to a more or less sharply defined luminous boundary. The luminous coating on the cathode is produced by the ionisation of the atoms of residual gas and the union of the electrons from the metal with the positive ions, with liberation of a further jet of electrons* starting from the neighbourhood of the cathode with velocities of the order of that of light.

2. The dark space is a measure of the mean free path of the electrons, and its outer luminous margin is the scene of the collisions between free electrons and the column of positive ions. It varies in size with the degree of exhaustion. At a pressure of about 4 mm. it begins to appear as a narrow space, a fraction of a millimetre removed from the negative pole, and grows larger as the exhaustion increases. At a pressure of about 3 mm. the margin of the dark space is about 4 mm. from the negative pole. At an exhaustion of 0·25 mm. it is about the best size for such work as I now describe. When the exhaustion is pushed further, the outer boundary becomes indistinct and soon fades away, the dark space now filling the tube, the walls of which glow with a phosphorescent light. It is to the phenomena occurring within this dark space that I have devoted years of work, and I now have the honour of presenting to the Society some account of the results of my prolonged investigations; in parts they lead to conclusions which have been already made public by other observers.

* Not long before his death, Sir George Stokes proposed to me to adopt a systematic nomenclature in this branch of research, and suggested the following:—

"Ray—A disturbance propagated in the ether.
Jet—A discharge of electrons.
Emanation—To include both Rays and Jets."

(The term *Emanation* is now appropriated to Rutherford's radio-active gas.)

"A cathode *jet* of electrons impinges on a metal and causes it to emit (X) *rays*. A self-luminous *emanation* from a radium-barium salt consists of *rays* of light and *jets* of electrons."

3. Fifteen years ago* I delivered an Address in which I described experiments undertaken to see how the positive and negative charges were distributed in vacuum tubes carrying a high tension current. At that time the electron theory was unknown, and my descriptions were given in the language then in use. What I then spoke of as "a stream from the negative pole," "negative molecules," "negative atoms projected violently from the negative pole," "ultra-gaseous state of matter," "radiant matter," etc., may now be included in the term "electrons." As the experiments I more particularly wish to bring before the Society arise out of my antecedent work, I will briefly describe some which are necessary to the proper understanding of the subject, merely translating into modern terms language which now has become archaic.

It is my hope that the experiments here described may be worthy of record as illustrating or testing the principles of the quantitative theories that have been elaborated to represent the phenomena.†

The Dark Space at Pressures down to 0·1 *mm.*

4. I had been examining the electrical condition of the interior of a vacuum tube carrying an induced current, by means of idle poles passing through the glass at different points.

A tube was made as shown in fig. 1. A is the negative pole, constructed so that it can slide to and fro along the narrowed axis of the tube by tapping the end, metallic contact being maintained by means of a fixed and movable

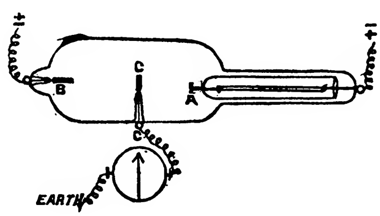

FIG. 1.

sliding wire, as shown; B is the positive pole; C is an idle pole. A and C are flat discs of aluminium, B is a short piece of aluminium rod. In these experiments C was connected to earth through a reflecting galvanometer‡ D E.

* 'Journal of the Proceedings of Electrical Engineers,' Part 91, vol. 20.

† *Cf.* J. J. Thomson, 'Conduction of Electricity through Gases,' 2nd ed., 1906.

‡ The galvanometer shown is merely diagrammatic. In these and the following experiments several different instruments were used, according to the sensitiveness required—low resistance needle, high resistance reflecting galvanometers, and Lippmann's electrometer.

The adjustable pole was put so that the idle pole was exactly halfway between the poles A and B. These were connected with the two poles of an induction coil, the break being unscrewed so that it would not act, and contact being made by hand. The tube was attached to the pump, but at first was not exhausted, my object being to see what effect differences of pressure had on the direction and intensity of the current passing from the idle pole to earth.

One contact of the coil was made by hand, sending one spark through the tube, A being the negative pole. No movement of the needle was seen. The coil commutator was reversed, making B negative, and another spark was sent through. No current passed to earth.

5. Exhaustion now proceeded, a spark being passed at intervals as the mercury gauge rose, but nothing was seen on the galvanometer until the pressure sank to 14·5 mm., when, in making contact, a faint jerk of the spot of light was noticed when terminal A was made anode, but none when it was cathode. At 13 mm. the same faint movement was observed, only a little stronger when A was anode, but none when A was cathode. At 12 mm., A being anode, the spot of light moved in the negative direction 36°, at 10 mm. it moved 34°, and at 7·5 mm. it moved 33°. Here for the first time, on making A the cathode, the galvanometer deflection was 17° in the positive direction. Observations were continued at intervals as the exhaustion rose, the deflection being + or − as the direction of the secondary current through the tube was reversed, and it continued to give positive and negative deflections down to a pressure of 0·0001 mm., when a current was still found to pass. These results are plotted on the diagram (fig. 2). Using

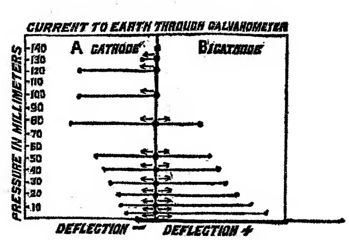

Fig. 2.

a Lippmann's electrometer instead of a reflecting galvanometer, I could detect + and − movements at considerably higher pressures than 14·5 mm.

Effect of Size of Tube on the Dark Space.

6. Does the size and does the shape of the tube in which the dark space is formed modify its appearance? By way of test I made an apparatus,

shown in fig. 3. The poles in A and C are of the same size, and are the same distance apart. The poles in B are cylindrical wires and are closer

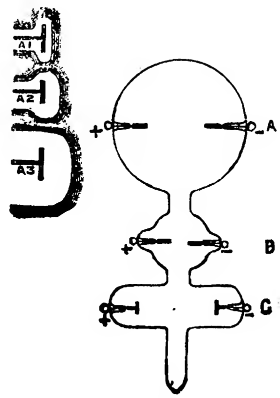

Fig. 3.

together. In this experiment the induction current was passed separately through each section of the apparatus.

A pressure was obtained so that the dark space in A was about 2 mm. from the face of the pole, as shown in A_1. On connecting the wires successively to B and C, there is very little difference in the appearance of their dark spaces, which resemble A_1. At a slightly higher exhaustion the dark spaces are as in A_2 in all three tubes, but the glass of the cylindrical tube, C, is much more phosphorescent than the others. On further exhausting, a considerable difference has come over the tubes. The dark space in A is well defined, and extends two-thirds the distance between the poles, as in A_3. In B the boundary cannot be seen, and the glass is slightly phosphorescent. The tube C appears to be almost free from gas or foggy appearance, and the whole tube glows with a bright green phosphorescent light.

Connecting the poles to the induction coil in parallel, so that the current passes simultaneously through the three, the sequence of phenomena is similar to that already described.

It therefore appears that the size of the enclosing tube does not influence the size of the dark space so long as this is to be seen, but as exhaustion proceeds the dark space is seen for a longer time and becomes of a larger size in a large tube, while with a small tube the dark space disappears when it gets near the wall, and the phosphorescence of the glass appears. I have already shown that the power of inducing phosphorescence seems to be at its maximum where the electrons and positive ions are in the act of

reuniting. Yttria and other phosphorescent bodies glow best at the edge of the dark space, and when the dark space extends to the sides of the tube the electrons unite with its positive ionic lining, and thereby cause the glass to phosphoresce.

Electrical Conditions about the Dark Space.

7. At the highest vacuum (0·0001 mm.), the tube being almost non-conducting, when I connected the idle pole with a delicate electrometer it always showed positive electrification, in spite of the idle pole receiving the full impact of the electrons shot from the negative pole, and for a long time I could get no indications of any negative charge inside the tube. Occasionally, when the vacuum was very high, I detected negative electrification; the following piece of apparatus was devised whereby this point could be investigated more closely.

8. Figs. 4, 5, and 6 show different phases of the same tube. The tube is cylindrical, and is furnished with three poles, A, B, and C. A and B are the

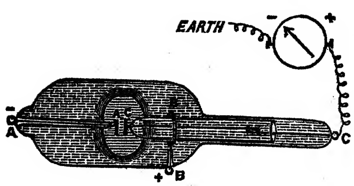

FIG. 4.

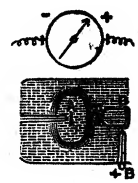

FIG. 5.

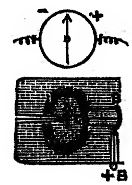

FIG. 6.

terminals, and C is an idle pole, capable of being moved along the axis of the tube by tapping the end, metallic contact being maintained by means of a fixed and movable sliding wire, as shown. The negative pole A is flat, and the positive pole ring-shaped; the idle pole C is also flat. The tube was exhausted to a pressure of 0·25 mm., at which point the dark space round the negative pole had the appearance shown in fig. 4. The idle pole C was then brought by tapping to a position well within the dark space, and it was connected to earth through a galvanometer. The indications showed that a strong negative current was passing from C to earth.

9. The idle pole was then brought to a position well outside the dark space, as shown in fig. 5. The galvanometer now indicated a positive current flowing from C to earth.

10. Tapping was continued, and the idle pole was gradually brought nearer to the negative pole. The indication of the galvanometer gradually became less, until, on reaching the dark space (as shown in fig. 6), no current was shown on the galvanometer.

11. Another tube (shown in figs. 7, 8, and 9) was made, having two fixed idle poles, C and D, A (−) and B (+) being the poles connected to the induction coil. Pole A was made movable like the idle pole in the former instance, and the tube was exhausted to 0·25 mm., when the dark space surrounding the negative pole was well defined. At first the movable − pole was so placed that the idle pole C was well inside the dark space,

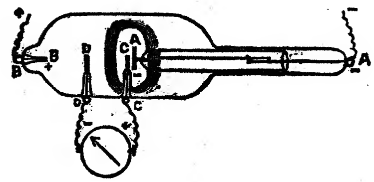

FIG. 7.

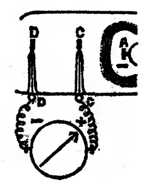

FIG. 8.

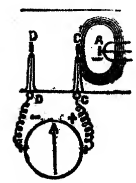

FIG. 9.

and the idle pole D outside it, as shown in fig. 7. On connecting the idle poles D and C through a galvanometer, the needle showed that a current passed in the direction that would be produced if C were zinc and D copper of a copper-zinc couple. An electroscope showed that each idle pole was charged positively.

12. The negative pole A was next placed in the position shown at fig. 8, so that both idle poles were outside the dark space. The galvanometer now showed that a current passed through it in the same direction as if C were copper and D zinc.

13. Finally, when the negative pole was still further removed, as shown in fig. 9, a point was found where no definite deflection could be obtained on the galvanometer, the needle oscillating irregularly a degree or two on each side of zero. This occurred when the pole A was in such a position that the outer border of the dark space just reached to the pole C. The electroscope still showed both poles to be positively electrified.

14. A tube was made as shown in fig. 10. The terminals of the tube are shown at A and B. B is the positive pole, consisting of a short thick piece

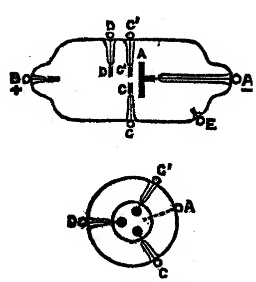

FIG. 10.

of aluminium wire. The negative pole A consists of a flat plate of aluminium, supported near the middle of the bulb on a wire guarded in a glass tube. C and C′ are small flat aluminium discs, 3 mm. in diameter, held at the ends of guarded metal wires on the same level and 3 mm. from the negative pole. D is a similar pole, 6 mm. further from the negative pole. These three idle poles were so placed that they were not in each other's way, a clear space being between each and the negative pole. Seen in plan, their positions were as shown at the side (fig. 10).

The tube was exhausted till the dark space round the negative pole extended beyond and well enclosed the two poles C and C′. On connecting them through a sensitive galvanometer while the current was passing between A and B, no appreciable current was detected.

15. C and C′ were now joined by an outside wire, so as to make one pole of them. They were connected with the galvanometer, and pole D was joined to the other side of the galvanometer.

Air was let in and exhaustion was continued till the dark space was about 2 mm. from the negative pole, as in fig. 11. The galvanometer showed that a current passed as if C C′ were copper and D zinc, giving a deflection of +186° (arbitrary scale).

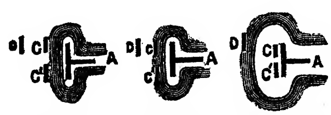

FIG. 11. FIG. 12. FIG. 13.

A little further exhaustion slightly increased the size of the dark space, and the deflection of the galvanometer sank to +86°. A few more drops of mercury passed through the pump brought the deflection down to +60° The dark space now was beginning to enclose the two poles C C′. A few more drops of mercury passed, and the galvanometer showed only a slight flicker, a degree or two one side and the other of zero, the appearance being as in fig. 12. At a slightly higher exhaustion the deflection became negative, −62°. Exhaustion was continued until the outer edge of the dark space commenced to touch the idle pole D (as in fig. 13), when the galvanometer deflection was −196°, as if C C′ now were zinc and D copper. The vacuum was pushed a little further, and the deflection became −133°. A little further it dropped to −86°, the dark space becoming large and indistinct, seeming to fill the bulb, and the green phosphorescence of the glass also becoming apparent. At a higher exhaustion the deflection was again zero, and on pushing the vacuum till the whole bulb glowed green, a steady current of +155° was shown in the opposite direction. At the highest

exhaustion I here obtained, the bulb being almost non-conducting, no current passed through the galvanometer.

16. Another pole, E, was now added to the tube below the negative A (fig. 10), and the experiments were repeated, using A (−) and E (+) as the poles for the induction current. The galvanometer deflection was taken between the idle poles C C′ and D. I thought it probable that the positive ions in the last experiment, beating in a stream from B to the idle poles, might have complicated the observations of current direction, hence the pole B was not used. The appearance of the dark space was practically the same at the different exhaustions as it was in the previous instance, and the deflections of the galvanometer were successively as follows:—20°+, 25°+, 22°+, 0°, 200°−, 130°−, 200°−. Here the green phosphorescence of the tube commenced to appear. 20°− ; at this degree of exhaustion the tube was almost non-conducting.

Relation between Pressure and Current in Dark Space.

17. I sought to ascertain the pressure at which the change from positive to negative took place, and the appearance of the dark space on one side and the other of the critical pressure.

A "dark space" tube was made as shown in fig. 14, and was sealed on to the pump by the side of the working tube (fig. 10) in which the experiments were tried. This "dark space" tube was used solely as an indicator of the changes in the appearance of the dark space when the galvanometer indications were taken during the experiments in the working bulb. A

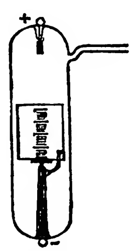

Fig. 14.

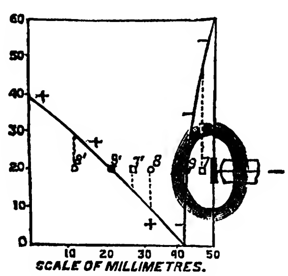

Fig. 15.

mica scale, divided into millimetres, was fixed across the centre of the negative pole, so as to enable measurements of the dark space to be obtained. By means of this tube, exhausted simultaneously with the working tube and actuated with the same induction coil, the distance of 2·5 mm. from the outer edge of the dark space to the flat pole was verified. It was noticed that when close to the critical pressure, but with a slight positive current, the

edge of the dark space was fairly sharp, but that when the change in deflection took place it was accompanied by a loss of sharpness of the outer boundary.

The radius of the dark space in this particular tube (fig. 10) was 2·5 mm., but with the idle pole C further from the negative pole the dark space would have to be larger to reach it, and the critical pressure would have to be a little higher.

The result of a ceaseless series of experiments with many kinds of vacuum tubes, and galvanometers and electroscopes of varying sensitiveness, is that the direction of the current between the two idle poles C and D changes as one of them gradually comes into the dark space. The following explanation appears to me reasonable, and to account for all the facts hitherto observed.

18. In fig. 15 I show diagrammatically in the form of curves the distribution of the negative and positive potential in the interior of the vacuum tube during the experiments illustrated in figs. 7, 8, and 9. The negative pole and dark space are shown at the right. The steep curve on the right represents negative and the curve on the left positive potential. The excess of electrons extends only to the edge of the dark space, the rest of the tube being positively charged.

The square dots marked 7 7′ show the position of the idle poles in fig. 7, where one pole is well within the dark space and the other outside it. It will be seen that pole 7 has a strong negative potential and pole 7′ a positive potential. In this case a current flows through the galvanometer connecting 7 and 7′, in the same direction as it would were 7 zinc and 7′ copper.

In the next position the idle poles are represented by hollow dots, 8 and 8′, as in fig. 8, where both poles are well outside the dark space; a current flows through the galvanometer as if 8 were copper and 8′ zinc.

Finally the solid dots 9 9′ show the positions of the idle poles in fig. 9, where one pole is on the edge of the dark space and the other outside. Here, therefore, the galvanometer shows no current.

Action of the Walls of a Vacuum Tube.

19. In studying the movements of the electrons in the dark space, it must be borne in mind that the distance of the walls of the vacuum tube from the cathode materially influences the appearance of the luminous phenomena in the interior.

To show the force of this influence, I sealed in tube, fig. 16, two exactly similar phosphorescent screens, C and D. At one end of each screen is a mica gate, E E′, to stop all phosphorescent action except in the centre of the screen. A flat pole faces each A A′ gate. Another pole is at B. C is one of the

screens in the narrow part of the tube, and therefore close to the walls. The other screen, D, is in the spherical portion, and therefore far removed from the walls. The poles A and A′ are connected and made negative poles, the pole B being the positive. On passing the current at a pressure of 0·001 mm., the electrons stream with a very high velocity from the two negative poles and produce phosphorescent effects. The screen D, in the globular part,

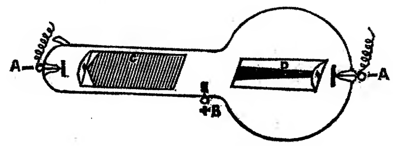

FIG. 16.

shows a narrow sharp streak of light, proving that here the electrons are free to follow their normal course straight from the pole, with no appreciable interference till they strike the screen. In the cylindrical part of the tube, however, the positive ions on the inner side of the glass drag the electrons from their normal course, with the result that the stream widens out sufficiently to cause nearly the whole surface of the screen C to glow with a uniform subdued phosphorescent light.

Dark Space Phenomena at the Lowest Attainable Pressures.

20. In a U-shaped vacuum tube at a moderately high exhaustion the stream of phosphorescent light marking the path of the electrons stops abruptly at the bend, and no appearance of turning round the corner or of reflection from the surfaces of the bend can be detected.

In a vacuum approaching the non-conducting stage, some of the electrons succeed in turning the corner somewhat by reflection, or produce by collisions others which do so, and pass a considerable distance along the further limb of the tube. These stray streams are still able to produce phosphorescence when falling on glass, sulphide of calcium, or yttria.

I have tried many ways of detecting the presence of these wandering electrons, and in the experiments now to be described I used photography to aid in their detection.

Photography inside the Vacuum Tube.

21. A photographic film exposed to the emanations inside a vacuum tube is strongly affected. Here we have positive ions, electrons, and Röntgen rays acting together, and I endeavoured to differentiate the effects of these three streams, analogous to the α, β, and γ rays of radio-active substances.

Experiments were instituted at first to see if the electrons which had lost much of their original velocity would affect a photographic film when it was out of the line of fire.

A **U**-shaped tube was made, as shown in fig. 17, A being the negative pole and B the positive. At the further end a flat plate of glass is cemented

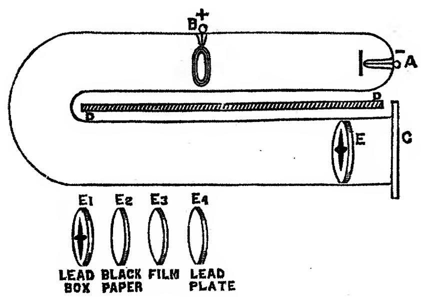

FIG. 17.

on. E is a lead box containing a photographic film, built up in the following manner:—The lead is 0·5 mm. thick, and the finished box is 20 mm. diameter. E_1 is a disc of lead, 2 mm. larger in diameter than the finished box, and having a star cut out of the centre. A disc of black paper, E_2, is put next the star disc, and a photographic film, E_3, is put next to the paper, the sensitive side of the film facing the star. E_4 is a plain disc of lead acting as a backing to the sensitive film. The whole put together in the above order, the edges of the front disc of lead are turned over the back. The lead box so packed is put into the further arm of the tube (which may be called the *laboratory* end) in an upright position, as shown, the stencil star facing the bend of the tube. A thick plate of brass is interposed at D D′ to cut off any Röntgen rays which might otherwise fall on the sensitive film.

The tube was well exhausted and carefully heated, but not to a sufficiently high temperature to injure the sensitive film. When the sound of the pump showed that the vacuum was high, the current was turned on for a minute. Gas was immediately given off, and the operations of exhausting and passing the current were repeated many times till a high vacuum was produced, the glass phosphorescing a bright green. The current was then kept on for 30 minutes, the pump working occasionally to prevent the vacuum deteriorating. When finished, and air let in, the lead box was removed by the window C.

On development, a good image of the star was seen, the rest of the film being unaffected.

22. The experiment was repeated, using a disc of aluminium-foil 0·2 mm. thick instead of the black paper E_2. After a high vacuum was reached, the current was kept on, as before, for half an hour. On development, a good image of the star was seen.

23. At a very high exhaustion in a darkened room, green phosphorescence of the glass can be detected to the end of the laboratory limb of tube. At the further end the action is very faint and difficult to see. Still the experiment proves that electrons in diminished numbers can get so far. I imagine that the velocity of impact which will produce phosphorescence of glass will also generate Röntgen rays when the electrons are suddenly arrested. A photographic film facing the bend of the tube and backed with metal is darkened by the rays, and I now sought to ascertain if a similarly disposed film at the further end of the film-holder would be also affected.

24. This experiment was repeated, using, as before, an aluminium disc behind the lead star, but the box was turned round so that the star and sensitive surface of the film faced the glass window C instead of facing the bend in the tube. The current was maintained for four hours and the pump kept going so as to keep the vacuum very high. At the lowest pressure at which the current would pass, a concentration of mobile green phosphorescent light appeared on the inner surface of the laboratory limb of the tube, a little before the place where the lead box stood. From the shape and appearance of the green patch of light it looked like a reflection of rays from the sides and curved part of the other limb of the tube. The patch was very sensitive to the approach of fingers, being driven sideways when a finger was within 3 inches of the glass. A cold metal rod held in the hand had the same effect, and a strong permanent magnet a similar action, but no stronger than the finger.

After four hours' exposure, the sensitive film was removed and developed. No image of the star was to be seen, but strong black patches at the edges of the film showed that an action had there taken place, apparently by leakage of electrons between the folds of the lead.

25. A larger box film-holder was made of brass, 2 mm. thick and 22 mm. external and 18 mm. internal diameter. Five small holes were drilled through the bottom of the box, and the brass back was accurately fitted so as to leave an internal space for the discs of film, aluminium, paper, etc. It was then packed as before. The first experiment was to try if the emanations would penetrate a thicker piece of aluminium-foil than was formerly used. (In the former case the foil was 0·2 mm., in the present case 0·5 mm. thick.) The box was put into the laboratory limb with the

film side facing the stream. After the tube was well exhausted the pump and current were kept going for two hours, a high vacuum being maintained all the time. On development, the film showed a good image of the five holes. The aluminium screen also was darkened under each hole in the brass.

26. Another similar experiment was tried with the same apparatus, the brass film-holder being packed, first with a thin piece of microscopic cover glass next the holes, then an aluminium-foil screen 0·5 mm. thick, then the sensitive film facing the aluminium and glass; finally the back cover was put on. The box was put in the laboratory limb with the poles facing the bend in the tube. The tube was exhausted and the current passed as before and kept going for three hours. On opening the box there was no visible discoloration of the glass film next the holes, but an image of the spots could be brought out temporarily by breathing on the surface. Nothing was seen on the aluminium film. On development, a good image of the spots was seen, and there was a little irregular darkening round the edge, occasioned probably by light conducted into the box by the glass circle.

27. It is fair to assume that the emanations I am dealing with in the laboratory limb of the U-tube consist of electrons whose velocity has been greatly diminished by collisions with atoms of matter. Besides these slow-moving electrons there must be Röntgen rays, for at the bend of the tubes bright green phosphorescence is seen on the glass—not only in the direct line from the negative pole, but a little further round the corner. The electrons suddenly arrested at the bend of the tube will also generate Röntgen rays, and some of these will be able to affect the film and penetrate an aluminium screen. Any positive atoms which may be liberated near the metal film-holder will be absorbed by the covering aluminium window.

Penetrating Power of the Rays or Jets.

28. The following experiment was tried to ascertain the penetrating power of the emanations affecting the sensitive film.

Thirteen discs of sensitive film were packed in a brass box, A, fig. 18, closed at one end, and at the other end a lead lid (shown at B), in the centre of which was cut a cross. Between the lead cross and the first disc of sensitive film a disc of aluminium (0·2 mm. thick) was interposed; all the films had their sensitive surfaces facing the cross. The packed box was put in the laboratory limb of the U-tube, the cross facing the bend, and the whole was exhausted to a high point, occasionally passing the current for a short time to drive off occluded gas. When the tube showed good phosphorescence the current was kept on for one hour, the pump being worked occasionally so as to keep the vacuum a little short of non-conducting.

On development, the image of the cross could be seen on the seven discs nearest to the bend of the tube, no action having taken place on the other six. The intensities of impression diminished from the first to the seventh.

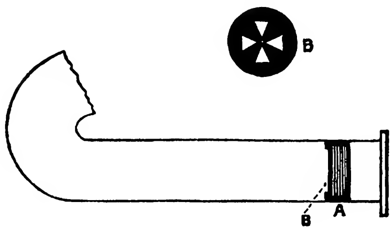

FIG. 18.

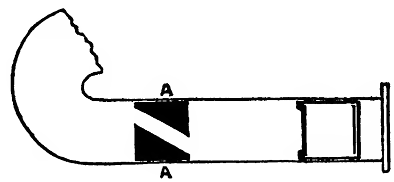

FIG. 19.

29. On examining the U-tube it was seen that if Röntgen rays were the cause of the action, they must have come from a part of the bend much out of the direct line of fire from the negative pole. But I have said that the glass phosphoresced right round the bend, and a part of this phosphorescing glass might be in a direct line with the box of films. I therefore devised a piece of apparatus which would probably settle the point as to the origin of these acting rays. The figure (fig. 19) shows the laboratory limb of the tube. A thick cylinder of type metal, A A (19 mm. long) is fitted into the tube in front of the film-holder, and through it is drilled a diagonal hole 7 mm. diameter. The film-holder is a brass cylinder 20 mm. long, closed at the further end, and in front having a thick lead cover with a 3-mm. hole through the centre, and a window of aluminium 0·2 mm. thick close behind it. Close to the aluminium is a sensitive film, and at the further end of the cylinder another sensitive film is fixed, a space of about 19 mm. separating the two. When the limb of the tube is packed ready for exhaustion, it is evident that no rays projected in straight lines from any part of the bent part of the tube can find their way through the diagonal hole and the aluminium window in the lead cover of the film-holder.

The pump was kept at work for some hours, with an occasional passage of the current, until the vacuum was at a high point, and non-conduction was commencing. In the dark the green phosphorescence of the glass could be traced completely round the bend and up to the thick metal plug, where it ended abruptly. At the bend a good image of the ring positive pole was seen on the glass, and, also, there was a sharp outline of the edge of the active arm of the tube. A careful examination of the different parts of the tube was made for Röntgen rays. These were seen issuing from all parts of the tube where the phosphorescence was full, and they could be detected coming also from the surface of the metal block facing the bend. Very faint indications

of Röntgen rays could be detected, also, coming from the lead and aluminium screens in front of the sensitive films in the laboratory end.

The current was passed and the pump kept going for $4\frac{1}{2}$ hours, during which time the tube was in its most active state. On removing the films and developing, no image whatever could be seen on either of them; they were quite clear and uninfluenced.

These experiments point to the conclusion that the emanations which act on the sensitive film are Röntgen rays emitted from the bend of the tube out of the direct line of fire from the negative pole. During the progress of the last experiment with the U-shaped tube, when the vacuum was high and the phosphorescence of the glass round the bend good, the shadow of the ring pole was seen, and the centre, where the direct jet of electrons from the negative fell, was hot and almost non-phosphorescent.

30. A narrow strip of sensitive film, safely enclosed in opaque black paper, was bent along the outside bend of the tube and held in place with string. It was exposed to the action for 10 minutes, then removed and developed. There was action over all parts, but the densest corresponded to the part inside the shadow of the ring pole.

Thus it appears that active emanations come from parts of the tube not in the direct line of fire from the negative pole, and experiments show that it is probable these are Röntgen rays, and if so, the rays will not diverge from a straight line when once started on their course, while jets of electrons with much diminished velocity will spread sideways. This is shown in the following experiment, which also illustrates the penetrating powers of the rays. The same U-tube was used as in previous experiments, but the film box was altered.

Röntgen Rays from Secondary Streams of Electrons.

31. A thick lead screen (fig. 20) was divided along its diameter so as to form two half discs, A and A′. These discs were put 5 mm. apart in front of the brass holder, and turned so as to expose a V-shaped opening, as shown. Next to the inner half disc is a disc, B, of aluminium 0·2 mm. thick, and close behind come five sensitive films, C. A space of 2 mm. now intervenes, and then come five more films, D, close to the back of the box. The films all face the bend of the tube, the box being near the window end. After good exhaustion the current was kept on for one and a-half hours, and on development an image of the V-shaped opening was seen on all 10 films. The parts of the film not exposed to the direct rays passing through the V aperture remained quite unaffected, showing that stray electrons had not turned round the edge of either half disc of lead. Careful examination

showed (1) that the intensity of the impression decreased as the rays had more and more films to penetrate; (2) that the image to a slight degree was multiple, showing that the rays did not come from a point, but from several adjacent parts of the bend of the tube; (3) that the 10 images were not of the same size, showing that the rays had appreciably diverged when passing through the films.

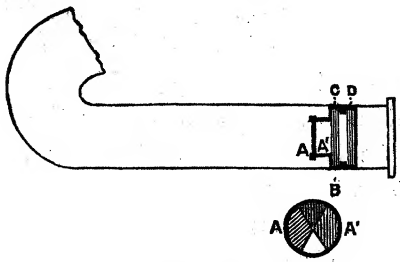

Fig. 20.

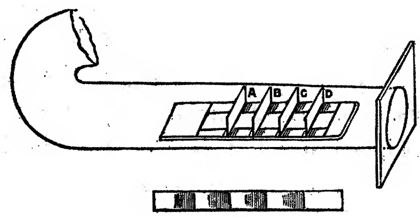

Fig. 21.

32. I wished to ascertain (1) if the emanations acted on the sensitive film when the face was not pointing towards the bend, and (2) if the action fell off as the distance from the bend increased. One of the experiments illustrated in fig. 17 shows that action does not take place when the sensitive film is turned facing the end of the laboratory limb, and having lead and aluminium obstructions guarding it; but something more was wanted before the action could be quite understood. A box of assay lead, 0·15 mm. thick, was made, 100 mm. long and 10 mm. wide, to hold the sensitive film, the aluminium-foil, and the lead screens. At one end a lead cap slipped on so as to keep the contents light-tight. Holes were cut through the upper layer of lead, in the form of a cross and five rectangles. A strip of sensitive film was first put in, then a strip of aluminium-foil 0·2 mm. thickness was put over it, and then came the upper surface of the box with holes as described. The box as packed was put into the laboratory end of the U-shaped tube, and a good exhaustion obtained. When the glass phosphoresced well the current was kept going for two hours. On removing the film and developing it, images of the six holes were seen. The impression at the end nearest the bend was the strongest, and the intensities of the other images gradually diminished towards the other end, the image of the last hole being extremely faint.

33. The greater part of the front of the lead box was now cut away, leaving a rectangular opening exposing most of the aluminium-foil beneath. Four upright pieces of lead-foil were placed equidistant along the opening, bridging it across and leaving square openings, A, B, C, D, separated by lead screens (as in fig. 21). A strip of sensitive film was first slipped in the

box, and in front of it was put an aluminium plate 0·2 mm. thick. The box was laid in the laboratory end of the U-tube, and after good exhaustion the current was passed for two hours. On development, an impression was seen beneath each square opening, as shown in the figure, getting fainter as the distance from the bend of the tube increased. It also was noticed that the impression in each square was not uniform in density, but fainter at the side further from the lead upright, and getting denser towards the lead upright. The effect was exactly as if emanations from the bend of the tube had struck each lead upright on the face, and then had been reflected back on to the film, passing through the aluminium screen. The explanation is obvious. Electrons have passed round the bend into the laboratory tube and, striking the face of each lead upright, have there generated Röntgen rays. These rays, not being intense enough to pass through the lead, have affected the sensitive film in front of the screen, the action being strongest at those parts of the film nearest the upright.

34. If this is the explanation, then the substitution of a thin sheet of aluminium for lead in one of the uprights would also generate Röntgen rays, but the rays would get through the aluminium and affect the film on both sides (40). By way of test the first two uprights of lead were removed and replaced by a square of aluminium 0·05 mm. thick, the rest of the packing being as before. After good exhaustion and exposure to the current for two hours at a very low pressure the film was removed and developed. The appearance confirmed anticipation. The film on each side of the aluminium-foil was darkened, as if the acting rays had emanated from both sides of the foil, whilst the appearance round the lead uprights remained as before. These experiments seem to prove that the action is one of Röntgen rays, that electrons which have lost much of their velocity still can generate these rays when they strike lead or aluminium, and also that rays so generated will not pass through lead-foil 0·15 mm. thick, but will penetrate aluminium foil 0·05 mm. thick.

Röntgen Rays from Phosphorescing Yttria.

35. In the experiments so far carried out the body emitting electrons has been the cathode, and the action on the photographic film appears to be due to the generation of Röntgen rays by the sudden arrest of electrons by a solid target, and the penetration of the screen in front of the film by these rays. It became of interest to see if a highly phosphorescent substance would emit Röntgen rays while it was phosphorescing. Ignited yttrium sulphate was now chosen as a target, and the experiment was conducted in the following manner :—

A brass chamber was made, 10 mm. long and 5 mm. wide (as shown at A, fig. 22), consisting of two cylinders fitting tightly one in the other. The

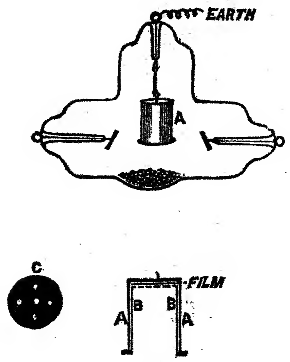

FIG. 22.

outer cylinder, A, is closed at the top, and the inner cylinder, B, is also closed at the top with a disc of brass, C, perforated with five holes. Removing the inner cylinder, a thick disc of lead is first pressed into it to form a bed for the back of the sensitive film; next comes a disc of sensitive film; on this is put a disc of aluminium 0·05 mm. thick—lastly, the inner cylinder is pushed home. The whole is suspended in a vacuum tube as shown, and connected to "earth" by a wire passing through the glass. The cylinder is suspended out of the direct line of fire from either pole, so that the phosphorescent rays from the yttria are the only ones that can get into the cylinder and shine on the perforated cover. Preliminary experiments having shown that the brass cylinder was liable to get very hot, and so injure the film, the outside of the tube was covered with blotting-paper, and a stream of cold water trickled over it throughout the experiment. When the vacuum was good and gas ceased to be liberated on passing the current, the latter was kept on for two hours, the current being alternating, so that each pole was cathode for half the time. On opening the tube and developing the film, a good image of the five holes was seen—a proof that the emanations from the yttria, during the act of phosphorescence, are also accompanied by rays capable of passing through thin aluminium and impressing themselves on a photographic film.

36. It is pretty evident from the results of the foregoing experiments that in the laboratory limb of the U-tube, far removed from the direct line of cathode stream, emanations are present which act on a photographic film, and that these emanations are of the nature of Röntgen rays generated in the neighbourhood of the bend in the tube. The following experiments were instituted to ascertain more definitely the nature of the emanations in

question, and also to see what happens when an aluminium plate is interposed in the line of direct radiations from a flat cathode instead of to the wandering electrons, as in previous experiments.

37. A vacuum tube was made with a flat aluminium cathode and a straight wire anode, as shown in fig. 23. The tube contains a cylindrical brass box, C C D D, closed at one end with a sheet of aluminium, C C, 0·05 mm. thick,

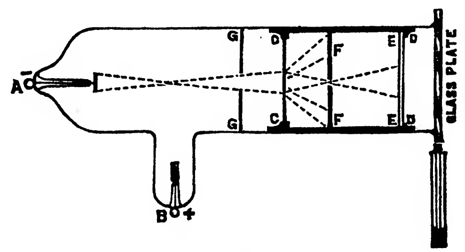

Fig. 23.

and at the other end by a thick plate of brass, D D, in front of which could be put a sensitive film, E E. Inside the box, and 20 mm. from the aluminium plate, C C, is a brass diaphragm having in the middle a 2-mm. hole. In the vacuum tube, 15 mm. from the outside of the box, is fixed a similar brass diaphragm, with a 2-mm. central hole.

A preliminary experiment before placing the diaphragm, F F, in position showed that the narrow jet of electrons passed through the hole in G G, and falling on the aluminium screen, C C, gave rise to emanations that darkened the sensitive film at E E uniformly over the whole surface. Thus, the emanation inside the box is no longer of the character of a jet of electrons, but proceeds in all directions from the surface of the aluminium disc. If, therefore, the diaphragm, F F, is put in position, as shown, it will limit the emanations which affect the sensitive film to a central circle about 8 mm. in diameter. The experiment was tried, a sensitive film being put in its place at E E. After good exhaustion the current was passed for two hours, the pump kept at work, and the vacuum being a little short of non-conducting.

The film, on development, showed a dark disc about 8 mm. diameter in the centre. Outside the edge of the darkened part was a wide space unacted on, showing that the emanation from the pole A, passing through the aluminium disc and the hole in F F, had pursued a nearly parallel direction.

Magnetic Deflection of Part of the Emanations.

38. The dark spot may have been caused by electrons from A or by Röntgen rays. It is not likely to have been caused by the positive ions, as these are arrested by aluminium much thinner than the 0·05 of a mm.

These two agents can easily be differentiated by a magnet. A preliminary experiment was tried to see how much magnetic deflection could be obtained, and whether it was sufficient to detect easily by photography. The apparatus shown in the last figure (fig. 23) was used. The aluminium disc, C C, was removed, the pierced diaphragms, G G, F F, were retained, the end D of the box was removed, and the photographic film in the last experiment was replaced by a phosphorescent screen. The tube was closed and, after exhausting for an hour, the current turned on. A central spot of phosphorescent light was seen on the screen. A magnet below the tube, in the position shown, pulled down the spot about 15 mm. At higher exhaustions the action of the magnet on the emanations was not so strong, but at the highest vacuum at which the current would pass they were appreciably deflected. The magnet was now adjusted so that at a high exhaustion the spot of light was brought down 10 mm. below its normal point; the position of the magnet was carefully registered, so that it could be placed in position at a future time.

39. The brass box now was fitted up as in the previous experiment (fig. 23), with a photographic film, E E, at the end, and the magnet put in position. Exhaustion was continued, the coil being turned on occasionally. When the vacuum was high the current was kept going for two hours. On developing the film, only a central spot of action was seen in the middle, but there was no sign of another spot drawn down below it, showing that the rays passing through the aluminium were not deflected by the magnet. This experiment was repeated several times with different exposures and varied forms of apparatus, always with the same result.

40. The explanation of the various results is now clear. The emanations inside the box are Röntgen rays, produced by the impact of electrons starting from the pole A. These electrons, falling on aluminium, a metal of low density and atomic weight, generate Röntgen rays, part of which penetrate the thin metal and radiate from the further surface. Had the metallic disc been made of metal of higher atomic weight, such as lead or platinum, the impact of electrons on it would equally have given rise to Röntgen rays, but these would have been confined almost entirely to the side struck by the electrons (34), and no action would have taken place inside the box.